

Diquark Higgs at LHC

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(Dated: September, 2007)

Existence of color sextet diquark Higgs fields with TeV masses will indicate a fundamentally different direction for unification than conventional grand unified theories. There is a class of partial unification models based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$ that implement the seesaw mechanism for neutrino mass with seesaw scale around 10^{11} GeV, where indeed such light fields appear naturally despite the high gauge symmetry breaking scale. They couple only to up-type quarks in this model. We discuss phenomenological constraints on these fields and show that they could be detected at LHC via their decay to either tt or single top + jet. We also find that existing Tevatron data gives a lower bound on its mass somewhere in the 400-500 GeV, for reasonable values of its coupling.

Introduction: The Large Hadron Collider (LHC), starting its operation within a year is expected to probe a new hitherto unexplored domain of particles and forces beyond the standard model. It can not only clarify some of the many mysteries of the standard model but also perhaps provide a glimpse of other new physics in the TeV energy range. The sense of expectation generated by this in the particle physics community has led to a burst of theoretical activity designed to explore great many theoretical concepts that perhaps the LHC can throw light on. They include ideas such as extra dimensions, supersymmetry, new strong forces, new Higgs bosons, new quarks and leptons etc. In this paper, we explore the possibility that LHC can throw light on a new kind of color sextet Higgs fields (denoted by $\Delta_{u^c u^c}$). Existence of such fields will indicate a fundamentally new direction for unification than the conventional grand unified theories. Indeed, there is a class of partial unification theories based on supersymmetric $SU(2)_L \times SU(2)_R \times SU(4)_c$ [1] model where $\Delta_{u^c u^c}$ fields appear with mass in the TeV range even though the gauge symmetry breaking scale is in the range of 10^{11} GeV due to the existence of accidental symmetries [2]. These models are interesting since they not only unify quarks and leptons but also implement the seesaw mechanism for small neutrino masses [3] and therefore provide a theoretical basis to contemplate the existence of TeV scale diquark Higgs fields. They make the unique prediction that $\Delta_{u^c u^c}$ fields couple only to the right-handed up-type quarks of all generations. These particles are also connected to baryon number violating processes such as neutron-anti-neutron oscillation [2]. Discovery of these particles would point towards quark-lepton unification at an intermediate scale rather than at the commonly assumed grand unification scale of 10^{16} GeV.

An interesting point about these particles is that they can be produced and detected at the LHC. Their couplings are however constrained by low energy observations. In this letter we

explore this topic and the main results of our investigation are:

- the present experimental information on $D^0 - \bar{D}^0$ mixing can be satisfied by setting to zero only the diagonal coupling of the $\Delta_{u^c u^c}$ to the charm quarks;
- the remaining coupling can be large enough so that the production rate in pp collision is significant and there are observable signal for the diquark Higgs field via its double top and single top plus jet production. Note also that a pp colliding machine such as LHC is more favorable for the production of these kind of fields compared to a $p\bar{p}$ machine e.g. Tevatron;
- the $\Delta_{u^c u^c}$ coupling matrix to quarks can be a direct measure of the neutrino mass matrix if the neutrino masses have a inverted hierarchy within our scheme, providing a unique way to probe the lepton flavor structure using the LHC.

Brief overview of model with naturally light $\Delta_{u^c u^c}$: In order to theoretically motivate our study of color sextet Higgs fields, we discuss how these “light mass” particles can naturally arise in a class of supersymmetric seesaw models for neutrino masses [3]. The seesaw mechanism extends the standard model with three right handed neutrinos and add large Majorana masses for them. The fact that the seesaw scale is much lower than the Planck scale suggests that there may be a symmetry protecting this scale. A natural symmetry is local B-L symmetry whose breaking leads to the right-handed Majorana neutrino masses. A gauge theory that accommodates this scenario is the left-right symmetric model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$. This model being quark lepton symmetric easily lends itself to quark-lepton unification a la Pati-Salam into the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$ [1]. It has already been shown [2] that within a supersymmetric Pati-Salam scheme, if $SU(4)_c$ color is broken not by $SU(2)_{L,R}$ doublet fields as was suggested in [1] but rather by triplets as proposed in [4], then despite the high seesaw scale of around 10^{11} GeV or so, there are light (TeV mass) sextet diquark of the type $\Delta_{u^c u^c}$.

To show this more explicitly, recall that the quarks and leptons in this model are unified and transform as $\psi : (2, 1, 4) \oplus$

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$\psi^c : (\mathbf{1}, \mathbf{2}, \overline{\mathbf{4}})$ representations of $SU(2)_L \times SU(2)_R \times SU(4)_c$. For the Higgs sector, we choose, $\phi_1 : (\mathbf{2}, \mathbf{2}, \mathbf{1})$ and $\phi_{15} : (\mathbf{2}, \mathbf{2}, \mathbf{15})$ to give mass to the fermions and the $\Delta^c : (\mathbf{1}, \mathbf{3}, \mathbf{10}) \oplus \overline{\Delta}^c : (\mathbf{1}, \mathbf{3}, \overline{\mathbf{10}})$ to break the $B - L$ symmetry. The diquarks mentioned above are contained in the $\Delta^c : (\mathbf{1}, \mathbf{3}, \mathbf{10})$ multiplet.

The renormalizable superpotential for this model has a large global symmetry of $U(30, c)$ and on gauge symmetry breaking, leads to all diquark Higgs fields and a pair of doubly charged Higgs bosons remaining light. In this theory, the gauge couplings become non-perturbative in the 10–100 TeV range and do not yield a high seesaw scale, as may be desirable. On the other hand, if we add an extra $B - L$ neutral triplet Higgs field $\Omega : (\mathbf{1}, \mathbf{3}, \mathbf{1})$ to this theory, the symmetry of the theory gets lowered and this helps to greatly reduce the number of light diquark states. The reduction of the global symmetry can be seen from the superpotential of this model $W = W_Y + W_H$ where

$$W_H = \lambda_1 S(\Delta^c \overline{\Delta}^c - M_\Delta^2) + \mu_i \text{Tr}(\phi_i \phi_i), \quad (1)$$

$$W_Y = h_1 \psi \phi_1 \psi^c + h_{15} \psi \phi_{15} \psi^c + f \psi^c \Delta^c \psi^c. \quad (2)$$

Note that since we do not have parity symmetry in the model, the Yukawa couplings h_1 and h_{15} need not symmetric matrices. This superpotential has $U(10, c) \times SU(2)$ global symmetry. When the neutral component of $(\mathbf{1}, \mathbf{3}, \mathbf{10} + \overline{\mathbf{10}})$ picks up VEV, this symmetry breaks down to $U(9, c) \times U(1)$, leaving 21 complex massless scalar fields. Since the gauge symmetry also breaks down from $SU(2)_R \times SU(4)_c$ to $SU(3)_c \times U(1)_Y$, nine of these are absorbed leaving 12 complex massless states, which are the sextet $\Delta_{u^c u^c}$ (the submultiplet of the Δ^c in Eq. (2)) plus its complex conjugate states from the $\overline{\mathbf{10}}$ representation above. Once supersymmetry breaking effects are included and higher dimensional terms

$$\begin{aligned} & \lambda_A \frac{(\Delta^c \overline{\Delta}^c)^2}{M_{Pl}} + \lambda_B \frac{(\Delta^c \Delta^c)(\overline{\Delta}^c \overline{\Delta}^c)}{M_{Pl}} \\ & + \lambda_C \Delta^c \overline{\Delta}^c \Omega + \lambda_D \frac{\text{Tr}(\phi_1 \Delta^c \overline{\Delta}^c \phi_{15})}{M_{Pl}}, \end{aligned} \quad (3)$$

are included, these $\Delta_{u^c u^c}$ fields pick up mass of order $\lambda_B \frac{v_{BL}^2}{M_{Pl}}$ which for $v_{BL} \sim 10^{11}$ GeV is in the 100 GeV to TeV range naturally. We denote the mass of $\Delta_{u^c u^c}$ by m_Δ .

Phenomenological constraints on $\Delta_{u^c u^c}$ couplings to quarks: The magnitudes of the couplings of diquark Higgs to up-type quarks are important for its LHC signal as well as other manifestations in the domain of rare processes. As is clear from Eq. (2), the sextet $\Delta_{u^c u^c}$ couplings to quarks, f_{ij} are also directly related to the neutrino masses, which provides a way to probe neutrino masses from LHC observations. Due to the existence of other parameters, current neutrino observations do not precisely pin down the f_{ij} . There are however other constraints on them.

To study these constraints, we define the $\Delta_{u^c u^c}$ couplings (f_{ij}) in a basis where the up-type quarks are mass eigenstates. A major constraint on them comes from the $D^0 - \overline{D}^0$ mixing

which is caused by the exchange of $\Delta_{u^c u^c}$ field:

$$M_{D^0 - \overline{D}^0} = \frac{f_{11} f_{22}}{4m_\Delta^2} \bar{c} \gamma_\mu (1 - \gamma_5) u \bar{c} \gamma^\mu (1 - \gamma_5) u; \quad (4)$$

The present observations [5] imply that the transition mass ΔM_D for $D^0 - \overline{D}^0$ to be $8.5 \times 10^{-15} \leq \Delta M_D \leq 1.9 \times 10^{-14}$ in GeV units. In our model, we can estimate this to be

$$\Delta M_D \simeq \frac{f_{11} f_{22}}{4m_\Delta^2} f_D^2 M_D \quad (5)$$

which implies that $\frac{f_{11} f_{22}}{4m_\Delta^2} \leq 10^{-12} \text{ GeV}^{-2}$; for a TeV delta mass, which is in the range of our interest, this implies $f_{11} f_{22} \leq 4 \times 10^{-6}$. If we assume that $f_{11} \gg f_{22}$, then for $f_{11} \sim 0.1$ or so, f_{22} is close to zero, which assume to be the case in our phenomenological analysis [6].

Next constraint comes from non-strange pion decays e.g. $D \rightarrow \pi\pi$ which are suppressed compared to the decays with strange final states. This bound however is weak. The present limits on such non-strange final states are at the level of $B \leq 10^{-4}$ [7], which implies $f_{11} f_{12} \leq 4 \times 10^{-2}$ for $m_\Delta \sim$ few hundred GeV to TeV range. This will be easily satisfied if $f_{11} \sim f_{12} \sim 0.2$.

Collider phenomenology: Due to the diquark Higgs coupling to a pair of up-type quarks, it can be produced at high energy hadron colliders such as Tevatron and LHC through the annihilation of a pair of up quarks. Clearly, a proton-proton collider leads to a higher production rate for $\overline{\Delta}_{u^c u^c}$ compared to the proton-anti-proton colliding machine. As a signature of diquark productions at hadron colliders, we concentrate on its decay channel which includes at least one anti-top quark (top quark for anti-diquark Higgs case) in the final state. Top quark has large mass and decays electroweakly before hadronizing. Due to this characteristic feature distinguishable from other quarks, top quarks can be used as an ideal tool [8] to probe other new physics beyond the standard model [9].

Since diquark couples with only up-type quarks, once it is produced, its decay give rise to production of double top quarks ($\overline{\Delta}_{u^c u^c} \rightarrow t\bar{t}$) and a single top quark + jet ($\overline{\Delta}_{u^c u^c} \rightarrow t u$ or $t c$). These processes have no standard model counterpart, and the signature of diquark production would be cleanly distinguished from the standard model background. We leave detailed collider studies on signal event of diquark (anti-diquark) Higgs production and the standard model background event for future works. Instead, as a conservative treatment, we calculate resonant production of diquark and anti-diquark Higgs at Tevatron and LHC and compare it to $t\bar{t}$ production in the standard model. The reason is that to observe resonant production of $\Delta_{u^c u^c}$ and measure its mass, it is necessary to reconstruct the invariant mass of the final state. In the double top quark production, if one uses the leptonic decay mode of a top quark, $t \rightarrow bW^+ \rightarrow b\ell^+\nu$, for the identification of top quark, with one missing neutrino and the hadronic decay mode for the other top quark to reconstruct the invariant mass [10], it becomes difficult to tell t from \bar{t} . However note that if one can use leptonic decay modes for both tops, one can distinguish $t\bar{t}$ from $t\bar{t}$ through charges of produced leptons.

First, we give basic formulas for our study on diquark Higgs production at hadron colliders. The fundamental processes in question are $uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow tt, tu, tc$ ($\bar{u}\bar{u} \rightarrow \Delta_{u^c u^c} \rightarrow \bar{t}\bar{t}, \bar{u}\bar{t}, \bar{c}\bar{t}$ for anti-diquark Higgs production). From Eq. (2), the cross section is found to be

$$\begin{aligned} \frac{d\sigma(uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow tt)}{d\cos\theta} &= \frac{|f_{11}|^2 |f_{33}|^2}{16\pi} \\ &\times \frac{\hat{s} - 2m_t^2}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2 \Gamma_{\text{tot}}^2} \sqrt{1 - \frac{4m_t^2}{\hat{s}}}, \\ \frac{d\sigma(uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow ut, ct)}{d\cos\theta} &= \frac{|f_{11}|^2 |f_{13,23}|^2}{8\pi\hat{s}} \\ &\times \frac{(\hat{s} - m_t^2)^2}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2 \Gamma_{\text{tot}}^2}. \end{aligned} \quad (6)$$

Here, we have neglected all quark masses except for top quark mass (m_t), $\cos\theta$ is the scattering angle, and Γ_{tot} is the total decay width of diquark Higgs, which is the sum of each partial decay width,

$$\begin{aligned} \Gamma(\bar{\Delta}_{u^c u^c} \rightarrow uu, cc) &= \frac{3}{16\pi} |f_{11,22}|^2 m_\Delta, \\ \Gamma(\bar{\Delta}_{u^c u^c} \rightarrow tt) &= \frac{3}{16\pi} |f_{33}|^2 m_\Delta \\ &\times \sqrt{1 - \frac{4m_t^2}{m_\Delta^2}} \left(1 - \frac{2m_t^2}{m_\Delta^2}\right) \\ \Gamma(\bar{\Delta}_{u^c u^c} \rightarrow uc) &= \frac{3}{8\pi} |f_{12}|^2 m_\Delta, \\ \Gamma(\bar{\Delta}_{u^c u^c} \rightarrow ut, ct) &= \frac{3}{8\pi} |f_{13,23}|^2 m_\Delta \left(1 - \frac{m_t^2}{m_\Delta^2}\right)^2 \end{aligned} \quad (7)$$

Note that the cross section is independent of the scattering angle because the diquark Higgs is a scalar.

With these cross sections at the parton level, we study the diquark production at Tevatron and LHC. At Tevatron, the total production cross section of an up-type quark pair ($u_i u_j$ where $u_{1,2,3} = u, c, t$) through diquark Higgs in the s-channel is given by

$$\begin{aligned} \sigma(p\bar{p} \rightarrow u_i u_j) &= \int dx_1 \int dx_2 \int d\cos\theta \\ &\times f_u(x_1, Q^2) f_{\bar{u}}(x_2, Q^2) \\ &\times \frac{d\sigma(uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow u_i u_j; \hat{s} = x_1 x_2 E_{\text{CMS}}^2)}{d\cos\theta}, \end{aligned} \quad (8)$$

where $f_u(x_1, Q^2)$ and $f_{\bar{u}}(x_2, Q^2)$ denote the parton distribution function, and E_{CMS} is the collider energy. Note that one parton distribution function is for up quark and the other is for the sea up quark, since it comes from an anti-proton (for a proton-anti-proton system such as at Tevatron). This fact indicates that at Tevatron the production cross section of diquark Higgs is the same as the one of anti-diquark Higgs, reflecting that the total baryon number of initial $p\bar{p}$ state is zero.

At LHC, the total production cross section of an up-type

quark pair is given by

$$\begin{aligned} \sigma(pp \rightarrow u_i u_j) &= \int dx_1 \int dx_2 \int d\cos\theta \\ &\times f_u(x_1, Q^2) f_u(x_2, Q^2) \\ &\times \frac{d\sigma(uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow u_i u_j; \hat{s} = x_1 x_2 E_{\text{CMS}}^2)}{d\cos\theta}. \end{aligned} \quad (9)$$

Here, both of parton distribution functions are for up quark in proton (both valence quarks), corresponding to a proton-proton system at LHC. Total production cross section of an up-type anti-quark pair ($\bar{u}_i \bar{u}_j$) is obtained by replacing the parton distribution function into the one for anti-quark. The initial pp state has a positive baryon number, so that the production cross section of diquark Higgs is much larger than the one of anti-diquark Higgs at LHC. The dependence of the cross section on the final state invariant mass $M_{u_i u_j}$ is described as

$$\begin{aligned} \frac{d\sigma(pp \rightarrow u_i u_j)}{dM_{u_i u_j}} &= \int d\cos\theta \int_{\frac{M_{u_i u_j}^2}{E_{\text{CMS}}^2}}^1 dx_1 \frac{2M_{u_i u_j}}{x_1 E_{\text{CMS}}^2} \\ &\times f_u(x_1, Q^2) f_u\left(\frac{M_{u_i u_j}^2}{x_1 E_{\text{CMS}}^2}, Q^2\right) \\ &\times \frac{d\sigma(uu \rightarrow \bar{\Delta}_{u^c u^c} \rightarrow u_i u_j)}{d\cos\theta}. \end{aligned} \quad (10)$$

The production cross section of the diquark Higgs and its branching ratio to final state up-type quarks depends on the coupling f_{ij} . This coupling is, in general, a free parameter in the model, and in our following analysis, we take an example for f_{ij} ,

$$f_{ij} = \begin{bmatrix} 0.3 & 0 & 0.3 \\ 0 & 0 & 0 \\ 0.3 & 0 & 0.3 \end{bmatrix}. \quad (11)$$

In this example, the phenomenological constraints on f_{ij} discussed in the previous section are satisfied with $f_{12} = f_{22} = 0$. This example gives rise to processes, $uu \rightarrow tt, ut$, that we are interested in.

Let us first examine the lower bound on the diquark Higgs mass from Tevatron experiments. We refer the current experimental data of the cross section of top quark pair production [11],

$$\sigma(t\bar{t}) = 7.3 \pm 0.5(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lum}) \text{ pb}, \quad (12)$$

and impose a constraint for the double top quark and a single top quark production cross sections through diquark Higgs in the s-channel. Since most of the $\sigma_{t\bar{t}}$ value can be understood as the standard model effect, the possible new physics should be in the uncertainty range of $\sigma_{t\bar{t}}$, we take the following conservative bound as

$$\sigma(p\bar{p} \rightarrow \Delta_{u^c u^c} \rightarrow tt, ut) \lesssim 1.5 \text{ pb}. \quad (13)$$

In our numerical analysis, we employ CTEQ5M [12] for the parton distribution functions with the factorization scale $Q =$

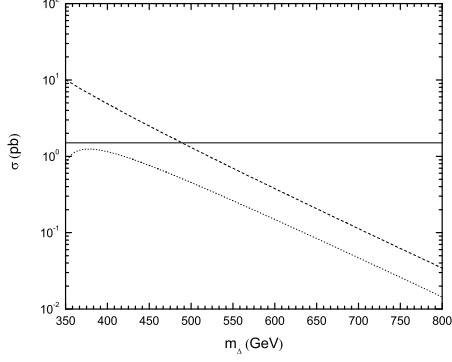


FIG. 1: The cross sections of tt (dotted line) and tj (dashed line) productions mediated by the diquark Higgs in s-channel at Tevatron with $E_{\text{CMS}} = 1.96$ TeV.

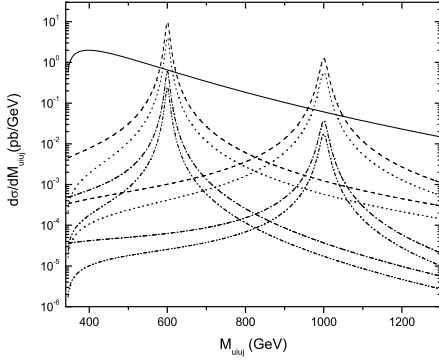


FIG. 2: The differential cross sections for tj (dashed line), tt (dotted line), $\bar{t}j$ (dashed-dotted line) and $\bar{t}\bar{t}$ (dashed-dotted-dotted line) as a function of the invariant mass of final state $M_{u_i u_j}$. The left peak corresponds to $m_\Delta = 600$ (GeV) and the right one to $m_\Delta = 1$ TeV. The solid line is the standard model $\bar{t}\bar{t}$ background.

$m_t = 172$ GeV. Fig. 1 shows the total cross section of tt and tu productions as a function of the diquark Higgs mass, with $E_{\text{CMS}} = 1.98$ TeV. The lower bound is found to be $m_\Delta \gtrsim 470$ GeV.

Next we investigate the diquark and anti-diquark Higgs production at LHC with $E_{\text{CMS}} = 14$ TeV. The differential cross sections for each process with $m_\Delta = 600$ GeV and 1 TeV are depicted in Fig. 2, together with the $\bar{t}\bar{t}$ production cross section in the standard model. We can see that the peak cross sections for the tt and tu productions exceed the standard model cross section while the $\bar{t}\bar{t}$ and $\bar{t}\bar{u}$ cross sections are lower than it. This discrepancy between the production cross sections of diquark and anti-diquark Higgs at LHC is the direct evidence of the non-zero baryon number of diquark Higgs. The charge of the lepton from leptonic decay of top quark or anti-top quark can distinguish top quark from anti-top quark.

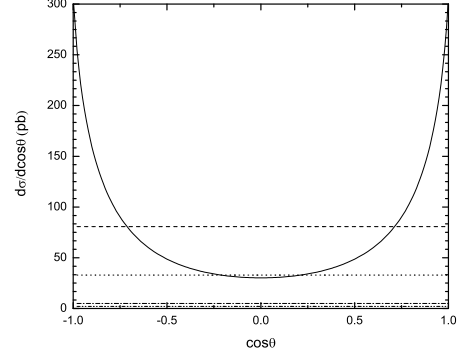


FIG. 3: Angular distribution of the cross section for $m_\Delta = 600$ GeV with $M_{\text{cut}} = 550$ GeV, together with the $\bar{t}\bar{t}$ production in the standard model. The same line convention as in the Fig. 2 has been used.

Counting the number of top quark events and anti-top quark events from their leptonic decay modes would reveal non-zero baryon number of diquark Higgs.

The angular distribution of the final states carries the information of the spin of the intermediate states. As shown in Eq. (6), there is no angular dependence on the diquark Higgs production cross section, because the diquark Higgs is a scalar particle. On the other hand, the top quark pair production in the standard model is dominated by the gluon fusion process, and the differential cross section shows peaks in the forward and backward region. Therefore, the signal of the diquark Higgs production is enhanced at the region with a large scattering angle (in center of mass frame of colliding partons). Imposing a lower cut on the invariant mass M_{cut} , the angular dependence of the cross section is described as

$$\begin{aligned} \frac{d\sigma(pp \rightarrow u_i u_j)}{d\cos\theta} &= \int_{M_{\text{cut}}}^{E_{\text{CMS}}} dM_{u_i u_j} \int_{\frac{M_{u_i u_j}^2}{E_{\text{CMS}}^2}}^1 dx_1 \\ &\times \frac{2M_{u_i u_j}}{x_1 E_{\text{CMS}}^2} f_u(x_1, Q^2) f_u\left(\frac{M_{u_i u_j}^2}{x_1 E_{\text{CMS}}^2}, Q^2\right) \\ &\times \frac{d\sigma(uu \rightarrow \Delta_{u^c u^c} \rightarrow u_i u_j)}{d\cos\theta}. \end{aligned} \quad (14)$$

The results for $m_\Delta = 600$ GeV with $M_{\text{cut}} = 550$ GeV are depicted in Fig. 3, together with the standard model result. Here the lower cut on the invariant mass close to the diquark Higgs mass dramatically reduces the standard model cross section compared to the diquark Higgs signal.

We now discuss the connection of the coupling f_{ij} to the neutrino mass. Once the $B - L$ symmetry is broken by $\langle \Delta^c \rangle$ along the $\nu^c \nu^c$ direction, right-handed neutrinos acquire masses through the Yukawa coupling in Eq. (2) and their mass matrix is proportional to f_{ij} . Therefore, f_{ij} is related to neutrino oscillation data though the (type I) see-saw mechanism which unfortunately involves unknown Dirac Yukawa couplings. When we impose the left-right symmetry on a model,

Δ^c is accompanied by $\overline{\Delta}^c : (\mathbf{3}, 1, \overline{\mathbf{10}})$, which adds a new term to the superpotential $f\psi\overline{\Delta}_L^c\psi$ with the same Yukawa coupling f_{ij} . Through this Yukawa coupling, the type II see-saw mechanism can generate Majorana masses for left-handed neutrinos. When the type II see-saw contributions dominate the light neutrino mass matrix becomes proportional to f_{ij} . In this case, there is a direct relation between the collider physics involving diquark Higgs production and neutrino oscillation data.

For the type II see-saw dominance, a sample value for f_{ij} that fits neutrino observations is given by,

$$f_{ij} = \begin{bmatrix} 0.27 & -0.48 & -0.47 \\ -0.48 & 0 & -0.38 \\ -0.47 & -0.38 & 0.2 \end{bmatrix}. \quad (15)$$

Again, this Yukawa coupling matrix is consistent with phenomenological constraints discussed in the previous section. The type II see-saw gives the light neutrino mass matrix via $m_\nu = f v_T$ with $v_T = \langle \overline{\Delta} \rangle$. For $v_T = 0.1$ eV, it predicts neutrino oscillation parameters to be:

$$\Delta m_{12}^2 = 8.9 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{23}^2 = 3 \times 10^{-3} \text{ eV}^2, \\ \sin^2 \theta_{12} = 0.32, \quad \sin^2 2\theta_{23} = 0.99, \quad |U_{e3}| = 0.2,$$

which are all consistent with the current neutrino oscillation data [7]. Here the resultant light neutrino mass spectrum is the inverse hierarchical. For $f_{22} \ll 1$ as required by $D^0 - \overline{D}^0$ mixing data, analytic and numerical studies show that only the inverse hierarchical mass spectrum can reproduce the observed neutrino oscillation data for the type II seesaw case.

We have performed the same analysis as before for this case and find the lower bound on the diquark Higgs mass from Tevatron data to be $m_\Delta \gtrsim 450$ GeV, which is a little milder than before. In this case, the peak cross section of only the single top + jet production exceeds the $t\bar{t}$ production cross section of the standard model. The differential cross section of Eq. (14) is independent of the scattering angle, and we find $d\sigma/d\cos\theta = 60.6$ pb for the single top + jet production for $m_\Delta = 600$ GeV with $M_{\text{cut}} = 550$ GeV.

Finally, we comment on spin polarization of the final state top (anti-top) quark. Because of its large mass, top quark decays before hadronizing and the information of the top quark spin polarization is directly transferred to its decay products and results in significant angular correlations between the top quark polarization axes and the direction of motion of the decay products [13]. Measuring the top spin polarization provides the information on the chirality nature of top quark in its interaction vertex. It has been shown that measuring top spin correlations can increase the sensitivity to a new particle at Tevatron [14] and LHC [15]. In the diquark Higgs production, it is very interesting to measure the polarization of top (anti-top) quark in the single top production. Only the right-handed

top quark couples to diquark Higgs and the top quark produced from diquark Higgs decay is right-handed state, while top quark from the single top production through electroweak processes in the standard model is purely left-handed.

We like to thank K. S. Babu, T. Han, K. Smolek and C. P. Yuan for useful discussions. The works of R.N.M. and H.B.Y. are supported by the National Science Foundation Grant No. PHY-0652363. The work of N.O. is supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan (#18740170).

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